RAPIDLY DEPLOYABLE STRUCTURES IN COLLECTIVE PROTECTION SYSTEMS

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ABSTRACT

The United States Military has a high need for rapidly deployable, lightweight, soft-walled structures that are capable of providing rugged protection from chemical and biological (CB) warfare agents. The versatility of these structures serve command and control, medical, and rest and relief functions with minimal time and effort. Speed and ease of deployment are critical due to the time constraints involved in a contaminated environment. The theory of rapidly deployable structures for collective protection has existed for decades, but the design challenges, logistics, and cost associated with such a structure have been a tremendous burden to overcome.

Many lessons have been learned from the various efforts and design considerations of the past. New advances are continually being made in textile structures and collective protection materials. The Soldier Biological Chemical Command-Natick Solder Center (SBCCOM-NSC) has a long-standing history as being in the forefront of these advances. New inflatable airbeam technology is emerging that offers new standards in reliability and affordability. The latest in lightweight rigid structures deploy quickly and offer a large deployed/stow ratio. Although current products provide protection, the need still exists for a rapidly deployable, lightweight, low cost, soft-walled battlefield tent that provides CB protection. This system must be made available to the widest number of troops possible. Through technology-based programs at NSC, several efforts are dedicated to overcome these challenges and develop the state-of-the-art rapidly deployable collective protection system.

I. INTRODUCTION

The threat of nuclear, biological, and chemical (NBC) weapons has only increased since the United States military first encountered them in World War I. Since then, the use of such weapons has expanded from the battlefield to sites of public terrorist attacks. Targets range from handfuls to the thousands. With this increasing threat, adequate protection must be made available to the widest number of troops possible. Collective protection is a means of providing an environment protected from NBC warfare agents for a variety of functions. Individuals can carry out tactical functions, such as communications or medical care, without the hindrance of individual protective equipment. Collective protection also provides a clean environment for rest and relief in the battlefield. To better serve military functions, collective protection must be rapidly deployable with minimum logistics to keep up with the mobility of military endeavors.

The current concept of collective protection creates a contaminant-free area by isolating it from the external environment and continuously providing clean air. The contaminant-free area is maintained at a pressure slightly higher than atmospheric pressure to ensure any leaks are released externally. This overpressure is consistent with the impact pressure of a 25 mph wind on a vertical wall, which is equivalent to 0.3 in. H_2O gage. It is typically desired to set the shelter overpressure slightly above this value to ensure variations in shelter pressure do not compromise the required 0.3 in. H_2O.

The typical collective protection system is comprised of a shelter, blower, gas-particulate filter, protective entrance, and environmental control equipment. Protective shelters may be a variety of shapes, sizes, and materials. The blower combined in series with the gas-particulate filter provides clean air for overpressure and ventilation inside the contaminant-free area. There are two different types of filters that clean the air from contaminants. First, the particulate filter removes aerosol and particulate matter such as smoke, dust, and bacteria. The gas filter then removes gaseous toxic agents in the airflow. The protective entrance is an airlock that allows personnel to enter and exit the shelter with a minimum introduction of contamination into the enclosure. The protective entrance is typically maintained at an overpressure 0.1 inches H_2O below the rest of the shelter in order to maintain the flow of air to exit via the door. Residence times inside the airlock are based on the time required to achieve a three-log reduction in the concentration of air-born contaminants.

The Collective Protection Directorate (CPD) of the Natick Soldier Center (NSC) is dedicated to the development of the latest in shelter technology. A successful structure takes into account all demands and requirements associated with its function. These functions may include logistics management, personnel protection, feeding, maintenance, communications, and medical. Sustainability and depolyability are two of the U.S. Army's main objectives. When weapons of mass destruction are involved, protection is a primary requirement. The shelter is required to provide a barrier between the contaminated external environment and the clean internal environment. The M28 system, the currently used military collective protection, consists of a Saran® coated polymer liner that is fitted to the inside of a Tent Extendable Modular Personnel (TEMPER) tent. The M28 liner provides a protected internal environment, but the material of the liner and the tent adsorb agents and will not survive decontamination, therefore both the tent and the liner must be disposed of if exposed to an agent. Ideally a collective protection shelter will not adsorb agent, will be decontaminable, and will have NBC protection integral to the outer skin to rid the necessity of a separate liner.

In addition to protection from NBC warfare agents, the shelter must also sustain a range of environmental conditions. The structure of the shelter, whether it is supported by pressurized airbeams, tensioned cables, or a rigid metal frame, must remain functional in all weather conditions. Typically a shelter must remain standing and functional in winds up to 35 mph (gusts up to 65 mph) and a snow load of five to ten pounds per square foot (psf). Military shelters may also be exposed to vibrations, rain, extreme temperatures, solar radiation, ice, sand, and dust. Such environmental loads require sufficient anchoring to resist wind-driven lift and frame and skin combinations with exceptional strength and durability.

Versatility and adaptability are needed to meet the unique and unpredictable field tentage requirements of the military. To allow personnel to perform mission critical functions, the shelter must provide adequate useable space, unhampered by internal supporting poles and frames. Protective shelters must be designed for depolyability, especially with the time constraints involved in contamination situations. Whether it is a command center, a general-purpose shelter, or a medical facility the shelter must be easily transported and deployed. High mobility is achieved with low weight and packing cube as well as diverse transportability options. It must possess easy and quick erect and strike capabilities to minimize manpower and time requirements. Logistics must be minimized as much as possible by increasing life cycle and requiring minimal parts and maintenance. Blackout, camouflage, noise suppression, and electronic shielding are desirable traits to provide the stealth required in combat operations. Safety is always a primary concern when dealing with personnel shelters. The structure must be fire resistant and provide exits easy to access and use.

II. HISTORY

M-51 Collective Protection Shelter System

The first rapidly deployable collective protection shelter was designed in the 1960's in response to the weapons of mass destruction capabilities internationally. This system, the M-51 shelter system, consisted of a 1 ½ ton trailer (military standard model M105A2) which supported the shelter, power generator, environmental control units (ECU), and filtration equipment that service the shelter. It is a self-contained unit designed to provide collective protection for ten occupants against all known CB agents. Normal deployment occurred whenever a CB attack was anticipated or imminent. The protective shelter was a dual-wall, air supported structure that provided 200 $ft.^2$ floor space. Chemical protection was provided through the use of a Tedlar®/neoprene coated Dacron® laminated fabric and interior pressurization with filtered air. This system was designed for use as a command post, battalion fire direction center, battalion medical aid station, air operations center, communications center, and rest and relief station.

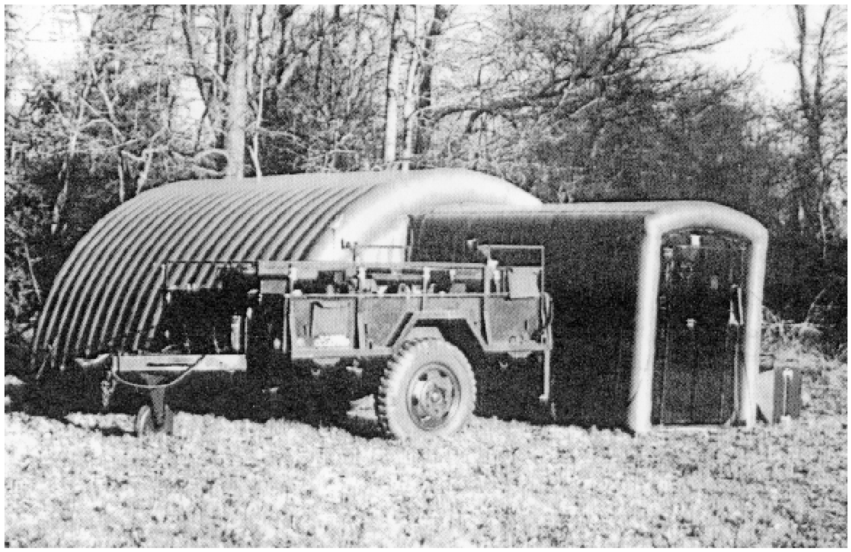

Figure 1. M-51 Collective Protection System.

The M-51 shelter was structurally supported by a double-fabric wall consisting of multiple fabric tube bladders inflated to 1.5 psi and shaped like a Quonset hut (see Figure 1). Erection using five men was specified as 30 minutes but users consistently reported erection times on the order of 60 minutes. Pressurization was automatically controlled by a switch-actuated solenoid valve arrangement and manually operated dampers located in the door between the shelter and the protective entrance. Two recirculation filters were placed in the protective environment; one in the protective entrance and the second in the shelter. The inside dimensions of the structure were 7.5 ft. high by 15 ft. wide by 14 ft. long (internal). The associated protective entrance, also air supported, was large enough (11 ft. long by 4 ft. wide by 6.7 ft. high) to accommodate litter and ambulatory patients. The entire shelter, including its protective entrance, weighed approximately 550 lbs. The entire system weighed 5705 lbs. including the trailer and had a packing volume of 797 cubic feet. The M-51 shelter and associated system equipment were type classified in July 1971.

While being state-of-the-art for its time, the users of the M-51 collective protection system were left with much to be desired. The 200 $ft.^2$ floor plan was insufficient space to allow its users to complete mission functions. With the semi-cylindrical shape, limited headroom close to the walls was also a hindrance. With a goal of 15 minute erection and an additional 10 minutes for CB hardening, the times approaching 60 minutes were unacceptable. The airlock doors had a threshold of six inches, which proved to be a bothersome trip hazard. This protective entrance had such a large volume that the air purge time was higher than feasible. Drawbacks for the 1 ½ ton trailer with associated equipment required a high logistics burden. The shelter system required constant operation of the trailer to provide air to the frame and the only source of fresh air for the shelter occupants. This constant operation caused occupant discomfort as well as provided a detectable noise and heat signature. Since the M-51 system did not have a dedicated vehicle, the crew and shelter were rendered immobile if the towing vehicle was relocated.

Due to these inefficiencies with the system, the U. S. Army dedicated efforts to design and develop an improved Battalion Aid Station (BAS). The design goals of an improved BAS were to increase the useable space as well as decrease the erection time. The protective entrance needed redesign to reduce internal volume and eliminate the trip hazard. Improvements would not require a continuous pressure source to the frame and would have vents to open in good weather, eliminating the required continuous trailer operation. Ideally the system would also have a dedicated vehicle integrated with the shelter.

Pressurized Rib Supported Battalion Aid Station

The BAS mobility requirements call for upwards of three moves per day. This type of mission critical requirement demands a shelter that is of a lighter weight, smaller packing cube, and faster strike/erect demands than the M-51 collective protection system. Advances were made on air-supported structures, which eliminated the required constant blower operation of the M-51 system. Developments in airbeams led to the feasibility of supporting a shelter with reduced structural members. Walter J. Krainski, Jr., U.S. Army Natick Research Development and Engineering Center, used Nonlinear Finite Element Structural Analysis (NONFESA) to optimize various airbeam structure variables for the BAS.[1]

The NONFESA approximates a pressurized arch using a series of small beam segments that conform to the curvature of an arch. This was considered a valid approach because it approximated the actual fabrication techniques of the time. All beams examined spanned a 18 ft. width in which stresses and deflections were measured and analyzed for a snow load of 5 and 10 psf and a steady wind of 30 mph. The 18 ft. span was chosen to provide the greatest amount of useable floor area and headroom as possible near the sides. A five-beam vertical arch structure (Figure 2) was analyzed and compared to a six-beam leaning arch structure (Figure 3) for pressurized airbeam diameters of 8, 11, and 14 inches at a number of inflation pressures between 1.5 and 10 psi.

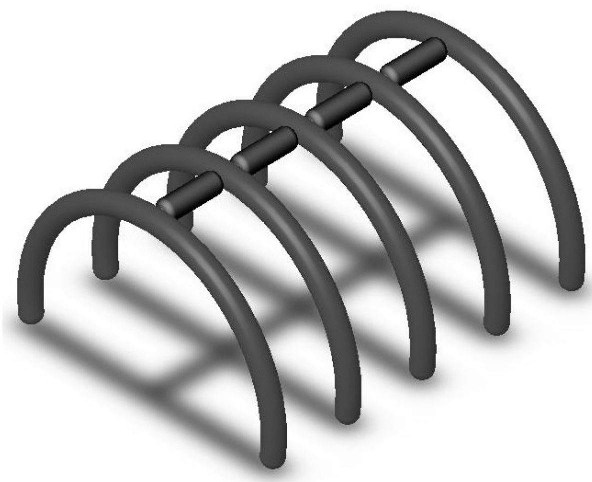

Figure 2. Vertical airbeam arch structure.

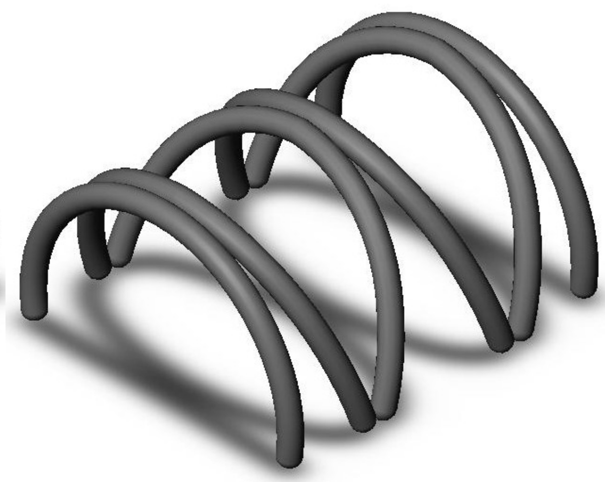

Figure 3. Leaning airbeam arch structure.

The NONFESA output consisted of beam forces, stresses, displacement, and rotations. Forces included axial force and torque as well as the bending moment. The stresses analyzed were the axial stress, bending, and average shear stress. Wind loads were investigated both with and without guy line braces and forces acting upon the tent skin were broken down into concentrated forces and appropriately distributed along each beam. After a number of computer-run iterations, it was concluded that the use of an 11 to 14 inch diameter beam with either configuration resulted in an acceptable design. The final chosen diameter depends on available inflation pressure capabilities. The leaning arch iterations required lower weights and lower inflation pressures to withstand the required loads.

This leaning arch design was used to fabricate a prototype of a pressurized rib supported BAS to serve as a potential replacement for the M-51 collective protection system (See Figure 4). This shelter design possessed a number of improvements over the M-51, one of which is the improved structural support system. The support system consisted of eight leaning airbeam ribs 14 inches in diameter and pressurized to 1.5 psi under normal conditions (6.0 psi under heavy snow). These parameters were determined by setting the tension in the arch wall due to inflation equal to the maximum compressive bending stress (also called wrinkle load) caused by environmental loading occurring along the outside of the arch. Instead of a single-layer beam material, these were fabricated using a bladder inside a structural sleeve. This bladder and sleeve concept was first explored and developed in design of the Transportable Helicopter Enclosure (THE). The bladder evolved from a 6.2 oz/yd^2 urethane film laminated nylon fabric to a 10 mil thick urethane film with no substrate. Its material, commonly used for air inflatable rafts, served as the air-holding member of the beam. The structural sleeve, made of a 10 oz/yd^2 uncoated polyester, did not provide air holding capabilities but served as the structural member of the beam. It also provided protection to the bladder during erection and striking. The airbeams required periodic repressurization, which was accomplished without starting the trailer system by using an auxiliary compressor. These small amounts of leakage from the ribs may have been caused by small pin-sized imperfections in the bladder or leakage through seams. The entire frame required approximately 330 cubic feet of air.

Figure 4. Air-Supported Battalion Aid Station.

Interior shelter dimensions were increased to 18 ft. wide by 25 ft. long by 10 ft. high to yield 400 square feet of floor space. Sufficient headroom close to the wall was achieved by raising the center of the beams 12 inches off the ground-line. Six vents were included to provide fresh air to the internal environment during good weather. The shelter material was also re-evaluated after lessons learned with the M-51 Tedlar®/neoprene coated Dacron® laminated fabric. The M-51 shelter material represented the state of the technology at the time, but it was heavy, stiff, lacked flame retardant properties, and was subject to flex cracking. Six different composite materials were identified as potential candidates: butyl nylon, Teflon®/Kevlar®, Tedlar®/vinyl coated Dacron®, Teflon®/Nomex®, polyester/Tedlar®/Kevlar®, and the original Tedlar®/neoprene coated Dacron®. Each material was tested and evaluated based on weight, chemical resistance, durability, fabrication characteristics, flexibility, flame resistance, material cost, and decontamination. A conclusion was made to use Teflon® coated Kevlar® due particularly to its improved flex durability and extremely low chemical resistance. Foil-Ray insulation was included to increase the thermal resistance of the tent. Foil-Ray is a bubble pack material with integral foil skins.

This system, unlike the M-51, had a dedicated vehicle that was integrated with the shelter upon deployment. A roped edge with clamping connected the tent to the back of the truck. The mating surface on the rear of the vehicle was permanently altered for this interface. The requirement for the 1 ½ ton trailer was also eliminated by using a ¾ ton trailer with the dedicated vehicle to support the new BAS system. A few packing modifications were made in order to repackage the ECU and filtration equipment onto the smaller trailer. The protective entrance dimensions were altered to reduce the purge time as well as the weight, cube, and erection time. Separate entrances were created for ambulatory patients and litter patients in order to reduce the volume of the chamber, therefore reducing the purge volume. Designing the fabric to roll onto lightweight aluminum doors reduced weight and cube from the 75 lb. rigid M-51 doors. These doors were easily installed in less then one minute using two people, reducing erection time. The anchorage system consisted of thin-walled fiberglass rods that connected into a continuous frame along the ground-line. Ten 24 inch wooden stakes anchored this manifold system to the ground. Unfortunately, the fiberglass manifold was difficult to assemble and the airlock and the vehicle obstructed some staking points.

The design of the air-supported BAS was successful in enabling a crew of four to perform emergency medical treatment in a chemically contaminated area and also met the mobility requirements. The improved airlock design, vehicle integration, and increased dimensions were successfully integrated while maintaining structural integrity under 30 mph winds and 10 psf snow load. Natural ventilation and rib pressurization were capable without running the trailer systems, reducing the noise, heat generation, and power requirements compared to the M-51. The anchorage system required some improvements to be more user-friendly and the rib material required re-investigation. The bladders proved to be difficult to fabricate, test, and install. The shelter package was unexpectedly large which proved difficult in storing it in the ambulance shell. New design iterations included a method to store the tent outside the vehicle with mechanical devices to aid in handling.

Frame Supported Battalion Aid Station

While the pressurized rib supported BAS was being developed, simultaneously a frame-supported design was also made. Most of the M-51 improvements integrated into the rib-supported version were also taken into account in the frame-supported version. These improvements include the new shelter material, airlock design and materials, increased dimensions, dedicated vehicle integration, and reduced trailer size. Both the frame-supported prototype and the air-supported prototype competed to replace the M-51 system. The frame supported BAS had the same geometric profile as the air supported version and was fabricated using the same Teflon® coated Kevlar® but was supported by five composite fiberglass rods with prestressed cables. The composite rod was bowed and prestressed via connection to a cable by means of a fabric web (see Figure 5). The fiberglass rod is one inch in diameter, which was chosen based on material properties and shelter dimensions. The design capabilities were compared to alternative materials like hot drawn steel and aluminum. Fiberglass provides the best combination of good flexibility and high allowable stress. A number of cross-sections were also considered, including rods, tubes, rectangles, and plates, but the rods proved to provide sufficient support with ease of use.

Figure 5. Frame-Supported BAS Rod and Cable Frame Member.

The use of the composite rod with the tensioned cable acted to separate the tension and compression members of the frame, simulating the relatively high section modulus of an I-beam. The tension transferred to the cable and the stress transferred to the rod was dependent on the loads applied to the shelter. For example, snow load increased cable tension and rod compression; therefore the maximum bending moment in each arch had to overcome the resultant stresses. Intermediate lateral supports were included to prevent buckling of the frame under heavy wind loads. Under wind load, the cable must remain in tension to overcome the compressive force and maintain the structural support of the bowed arch. Failure tests were conducted on the frame members to validate the design as well as to understand the breaking methods. The first sign of frame member failure was a cracking sound. The fibers at the failure continued to slowly break away until about 1/3 of the rod's cross-section were broken. No fiberglass shards broke away and the rod remained intact.

This shelter was also integrated to a dedicated vehicle (See Figure 6). The tent attached to the rear of the vehicle via Velcro connections. This was thought to be an improvement over the more difficult to use roped edge/clamping design of the air-supported version. This shelter weighed 282 pounds, which was significantly lighter than the air supported 450 pound shelter. The anchorage system was similar to the air-supported version. A metallized vinyl coated fabric, Durashade 4413, was used to provide increased thermal resistance.

Figure 6. Vehicle End of Frame-Supported Battalion Aid Station.

The frame supported BAS proved to be a lightweight, viable approach to the application. The improved airlock design (See Figure 7), increased dimensions, ventilation, dedicated vehicle integration, and reduced trailer requirements were all successfully incorporated. The weight and bulk of this system were significantly less than the air supported version, and the rigid frame weighed less than the frame of similar size traditional metal frame tents. The packing of the ECU and filtration equipment was slightly altered to reduce the trailer requirement from 1 ½ ton trailer to ¾. This system was also capable of being used without running the trailer system due to the integration of five ventilation ports. This BAS version did not require any maintenance once erected and the vehicle was directly accessible from the tent without leaving the protected environment.

Figure 7. Airlock End of Frame-Supported Battalion Aid Station.

There were, however, some drawbacks to the rigid frame prototype. The anchorage system, like that of the air-supported version, was difficult to put together and some corners had limited access during staking. The frame design was sufficient to withstand the necessary structural loads, but caused much concern with users. First, the frame was difficult to put together. The time and effort that was involved in shelter erection was disappointing, providing no advantages over the M-51 system. Second, the assembled frame contained a lot of stored energy. When assembled, the initial outer fiber stress equals 27,000 psi, the inner fiber stress equals –29,000 psi compression, and the cable tension equals 700 pounds. A lot of energy had to be put into the catenary system that tensioned the rod members, which proved to be awkward and difficult. Also, this high amount of stored energy posed a safety concern.

Trailerless Collective Protection System (TCPS)

As noted, a number of areas of improvement were identified during the development and fabrication of the Battalion Aid Station. While developing the first two units, an entirely vehicle mounted system was introduced to advance the state of design of the BAS. The TCPS was intended to perform the same function as the BAS: enable a medical crew of four to perform emergency medical treatment in a chemically contaminated area. A modified, dedicated vehicle supported this trailerless system. Taking advantage of the heating and cooling systems already present in the truck shell eliminated a separate environmental control unit. All standard equipment in the vehicle shell was removed and replaced with the blowers, filters, medical equipment, and auxiliary tent equipment. Mechanical system operations were optimized and streamlined so that they were all controlled from a central panel accessible from inside the tent and the vehicle. The tent was permanently attached to the back of the vehicle instead of having to be attached and unattached during strike and erect. A lifting mechanism consisting of two block and tackle assemblies and a lifting pipe dramatically reduced the strike and erect requirements. The shelter was simply lowered and unrolled directly from the rear of the vehicle. To further simplify shelter/vehicle interface, the back surface of the vehicle had a number of permanent interfaces including electrical, ventilation, environmental control, and air supply.

The shelter included in the TCPS was quite similar to that of the air-supported BAS shelter. It was smaller (18 ft. long by 18 ft. 2 in. wide), but was supported by six leaning arch pressurized ribs with 14 inch diameter and 2.5 psi. The blower was automatically activated when the rib pressure fell below 1.0 psi and would continue for one minute after 2.0 psi was reached (typically resulting in rib pressure 2.5 to 3.0 psi). Nine inches were added to the height of the shelter to allow necessary headroom close to the walls. This airbeam frame structure was designed to meet 30 mph wind loads and 5 psi snow load. To meet these loads, the bending stress was calculated using properties of the cylindrical arch and internal pressure is calculated by setting the tension in the arch wall equal to the maximum compressive bending stress. The design results were verified using finite element analysis before fabrication and full-scale testing. Due to previous concerns of shelter failure, the decision was made to separate each individual rib using check valves. Shelter weight was 300 lbs. and erection and strike was capable in 20 minutes using four personnel. The shelter material was the same Teflon® coated Kevlar® used in the previous BAS versions but the rib material was a urethane coated nylon fabric instead of the bladder and sleeve. The bladder and sleeve were expensive to build and difficult to use, so the single layer 12.4 oz/yd^2 was the chosen substitute.

The protective entrance was redesigned as two parallel airlocks, rather than the one chamber for both ambulatory and litter personnel. This new design significantly reduced the purge volume of the airlock, therefore increasing entry and exit rate. The airlock doors, similar to the previous versions, could be easily and quickly installed and removed. Using the leakage from the main shelter, no recirculation filter was required in the airlocks. The ambulatory airlock was supported by a 10 in. diameter pressurized rib integral to the rest of the shelter support system.

The shelter had four windows and two vents. The vents included an interior sealing flap and external weather sealing flap to maintain the protective environment when required. Floor drains were included near the corners of the shelter for internal cleaning. The vehicle provided 20,000 Btu/h cooling and 30,000 Btu/h heating and the CB filters caused a temperature increase of 10°F. In order to maintain a comfortable internal temperature in extreme temperatures, insulation was included in the system. A quilted insulation, consisting of alternating layers of polyester batting and metallized Mylar film, was fabricated to fit the interior of the shelter ceiling and sidewalls. The troublesome anchor tube frame was replaced with a catenary system that was anchored to the ground. Overall, the TCPS was much improved over previous BAS systems.

III. PRESENT DAY RAPIDLY DEPLOYABLE COLLECTIVE PROTECTION SHELTERS

Chemically and Biologically Protection Shelter (CBPS)

The Trailerless Collective Protection System (TCPS) evolved into what is now called the Chemically and Biologically Protected Shelter (CBPS, See Figure 8). The CBPS functions as both the battalion aid station (BAS) and the division clearing station (DCS). As the BAS, the CBPS is a single tent and vehicle with the primary mission of resuscitation, diagnostics, and stabilization. The DCS requires two CBPS systems complexed together with the same mission functions as the BAS but also includes limited surgical capabilities. The system has a dedicated High Mobility Medium Weight Vehicle (HMMWV), which provides power to the shelter via a hydraulic power transmission system. The CBPS improves upon the TCPS in many ways, including performance and cost.

Figure 8. Chemical Biological Protective Shelter.

The Teflon® coated Kevlar® shelter material sufficiently met the protection requirements but the rib material burned readily. This was replaced with a lightweight, bias ply, neoprene coated nylon fabric. An additional layer of neoprene was fabricated between the two plies of nylon to improve air holding. The endcaps of the beams were redesigned to prevent previously seen leakages. Further improvements in frame air holding were also made using a new dump valve design and manifold to improve the isolation of the pressurized air in the beams. The CBPS was successful in transitioning the one-piece woven airbeam from early development (6.2) into the first ever in production. In addition to the air holding in the airbeam frame, the air holding inside the protective shelter was also improved upon to rid the system of the excessive leakage. The window vents were eliminated and six non-openable windows were introduced. Ventilation would be achieved via screened side panels and doors. In addition to reducing the shelter leakage, this design change also simplified the fabrication of the shelter skin. The skin fabrication process was also altered to reduce shelter leakage. Instead of being fabricated using 28 separate fabric sections like previous designs, the CBPS utilized larger panels greatly reducing the number of seams. All seams were then taped on the interior and exterior to cover exposed fabric edges where contaminant wicking could occur.

The ambulatory airlock dimensions were adjusted to provide the minimum area that would allow a person to enter and close the door. This new design was supported by a single 10 in. diameter rib with two guy lines for lateral stability. The same lightweight, aluminum doors were used on the CBPS as the

TCPS with a timer built into the inner door. The TALP was redesigned to consist of two fabric tubes, one short tube on the interior of the shelter and a longer tube on the exterior. This new design has a purge rate of slightly less than three minutes to reach a three-log reduction in airborne contaminants in the ambulatory airlock and just over three minutes in the TALP, a significant improvement over past designs (See Figure 9). The DCS was also re-evaluated to integrate a new design into the CBPS. Past designs consisted of a connector sleeve that was permanently attached to the curved sidewall of the airbeam shelter. This extra material was too much weight hanging on the shelter and allowed water leakage into the shelter. The connector on the CBPS was redesigned as a removable fabric ring that is attached when desired (See Figure 10). This new design was capable of carrying the desired wind and snow loads without the use of an auxiliary frame and allowed position flexibility when connecting two systems.

Figure 9. Airlock End Chemical Biological Protective Shelter.

Figure 10. Two Complexed Chemical Biological Protective Shelters.

The CBPS system has successfully been tested from a number of different aspects including effectiveness, survivability, and user approval. During the late 1980's the CBPS system passed concept evaluation, user appraisal, engineering design, MANPRINT appraisal, and entry exit challenges. Since then the system has successfully completed production verification tests, pre-production qualification, production verification, customer tests, and user tests. This is the only airbeam collective protection system that has been used by soldiers and its quick erect and minimal logistics have proven quite favorable. During Limited User Test I and II, the CBPS was successfully complexed and integrated with the Forward Surgical Team and Division Clearing Station staff and equipment. In May 2002 the CBPS successfully completed Limited User Test II at Fort Hood, Texas and is in production.

Bea Maurer Inc. Base-X Expedition Shelters

Bea Maurer Inc., specializing in the design and production of deployable equipment for military and industry, joined efforts with World Shelters in the late 1990's to create the Base-X Shelter System. These shelters, although not military type-classified, are being directly purchased by a number of military users as a commercial off-the-shelf system. The Base-X Shelter System (See Figure 11) is a series of soft-walled tents supported by a one-piece, expanding, metal frame. These shelters use a "Buckminster'Fuller" type

Figure 11. Base-X Shelters.

of geodesic structure that offers reduced cube, weight, and deployment requirements in comparison to rigid frame structures of comparable strength and size. The family of shelters is available in a variety of widths, including 9 ft. 6 in., 14 ft., and 18 ft. For each shelter width, a length of 15 ft. or 25 ft. may be chosen. The shelter walls are at a slight angle and roof comes to a peak along the ridge (See Figure 12). The endwalls are completely removable for full complexing end-to-end. The shelters consist of a 10 oz./yd^2 outer skin with a 7 oz./yd^2 inner liner. A 12 in. dead air space exists between the outer skin and the liner to provide increased thermal resistance. The inner liner contains a number of user-friendly accessories such as an attached plenum for air distribution, pre-attached floor, and pre-wired electric distribution. Vinyl windows are openable from the interior of the shelter to expose screens. Windows and doors alternate on every 5 ft. side panel and doors are on each endwall. The Base-X family of shelters are fabricated with ducts on the sidewalls to interface with military standard environmental control equipment and power distribution.

Figure 12. Drash ST Series Design.

The most attractive qualities of the Base-X family of shelters are the weight, packed size, and set-up time. A 450 sq. ft. shelter weighs 445 lbs., folds into a package 37 cubic ft., and is set up in 19 minutes by only three people. The smallest of the shelters provides 143 sq. ft. floor space, weighs 235 lbs., packs to 24.5 cubic ft., and can be erected in nine minutes using two people. The shelter skin is attached to the collapsible metal frame, which is packaged with the staking kit and repair kit. A carrying bag is included for easy transport. Frame members are connected via clevis pins, therefore replacement of parts is fast, easy, and does not require special tools.

Base-X shelters are currently being used by the 101st Airborne Division's new Division Main Tactical Operations Center and have been used in a number of other Division, Brigade, and Battalion level units and Regiments among all active U.S. Armed Forces. The Base-X shelter systems are easily transitioned from a general-purpose tent to a collective protection system. The first CB protected Base-X shelter incorporating a CB protective liner will be demonstrated at the ColPro 02 Conference.

DHS Systems Drash Shelter

DHS Systems, since 1984, has created a family of quick strike and erect shelters entitled DRASH (Deployable Rapid Assembly Surgical Hospital). Commercial off-the-shelf DRASH shelters have been directly purchased by a number of military users for functions such as command post, tactical operations, communications, battalion aid stations, and forward surgical support. This family of shelters is applicable to such a variety of functions because it is lightweight, easily deployable, and modular. It is supported by a series of uniform parts made from Titanite® composite tubing in a geodesic configuration. The shelters are modular and are capable of complexing with other shelters and vehicles. The shelter skin is made from Xytex®, a high tenacity fabric that provides protection from the environment. It is abrasion resistant, water repellant, fire retardant, UV resistant, IR reflective, and provides blackout capabilities.

The Drash shelters, popular among military and commercial customers, consist of only three parts. The shelter skin and associated interior liner are both pre-attached to the shelter frame. The system also consists of a ground cover and interior flooring. A 402 sq. ft. shelter weighs 498 lbs. and packs into 44 cubic ft. It should be noted that both DRASH and Base-X shelters are not logistically supportable through normal military procedures as they have not completed the military type-classification process which ensures performance, durability, and safety.

Federal Fabrics-Fibers Inc. Low Pressure Woven Airbeam Structures

Federal Fabrics-Fibers Inc (FFF) is a small company (20 employees) located in Lowell, Massachusetts. FFF capabilities include extensive research and development of seamless, three-dimensional, woven textiles designed to encapsulate fluids under pressure. The NSC has a long standing history with FFF involving airbeam development, including the transition of their technology into the CBPS. The FFF airbeam is a woven material surrounding an air holding bladder inflated to low pressures. FFF began development on this technology during the early 1990's, but has made tremendous technological advances in materials, structures, and fabrication since then. The latest low pressure woven airbeam technology is displayed in the Advanced Command Center Module (AC2-MOD), a joint venture between FFF and the NSC.

The AC2-MOD (See Figure 13) is a small airbeam-supported structure measuring 20 ft. wide by 10 ft. high by 24 ft. long. The system is completely modular based on 12 ft. long sections. The AC2-MOD is based on two modules, but a third 12 ft. long section can be inserted to create a 36 ft. long shelter. The airbeams are integral to the shelter, hidden between the outer skin and inner liner. All airbeams in the frame are interconnected via cam lock fittings, therefore inflation occurs all at one point. Because all parts of the shelter frame and skin remain attached, set-up and take-down require minimal time and effort. This network of airbeams is arranged in such a fashion that the shelter is self-erecting. The bundle does not need to be unrolled from its tightly packaged bundle during erection. Once the blower is attached and turned on, the shelter unfolds and erects on its own. The only additional effort needed is for staking. This self-erecting feature is highly attractive for collective protection, especially if the shelter has to be erected in a contaminated area. If an area is already contaminated, personnel will be burdened by cumbersome individual protective equipment as they set up a protective shelter as quickly as possible. In this situation the AC2-MOD would provide a protected area for rest and relief or mission critical functions within minutes. This type of immediate response is also required in a situation where CB contamination is imminent or even suspected. The AC2-MOD is designed to interface with military standard environmental control and CB filtration equipment and is capable of holding an overpressure.

Figure 13. Advanced Control Center Module-36 ft. long.

With the self-erecting structural design complete, FFF was faced with the challenge of meeting all environmental loads while maintaining safety requirements. The use of guy lines off the endwalls of the shelter in addition to staking points along the sidewalls ensured secure anchoring during high winds and wind gusts. The sustainability requirement under 10 psf snow load had to be taken into account because the CBPS program specified only 5 psf. FFF fabricated a number of test beams that were used to determine the beam size and operating inflation pressure that would withstand the snow load. A compromise was made between inflation pressure, number of airbeams, airbeam spacing, and airbeam diameter. Using three sets of double arches, the 24 ft. long AC2-MOD required 14 in. diameter airbeams inflated to 18 psi to meet the snow load. Since FFF uses a margin of safety of three, they had to ensure their airbeam could sustain inflation pressures up to 60 psi. To accomplish this the airbeams were redeveloped from the fiber up. Dimension stable polyester (DSP) was chosen to replace the previously used polyethylene napthalate (PEN) due to its increased strength and reliability and lower cost. Because DSP is flammable, FFF developed a new yarn coating to incorporate a fire retardant agent into the polymer backbone. The yarn strength was increased from 1500 denier to 3000 denier to be more puncture resistant. A specialized injection molding machine was designed and fabricated for FFF to optimize a multi-material cam lock fitting to combine flexibility and strength at airbeam interconnects.

A number of accessories, intended to alleviate the workload of the end user, have been incorporated into the base shelter design. For example, the AC2-MOD contains military standard vestibule connectors to interconnect with itself, other military shelters, or vehicles. Windows are included on both endwalls that can be opened to expose a screen for ventilation or closed with a weather flap to provide blackout capabilities and protection from the environment. Sealable vents are located along the ridge and the groundline of the shelter to provide natural ventilation between the outer skin and the inner liner when desired. The dead air space between those two layers provides insulation to reduce heating and cooling requirements in extreme external temperatures. The FFF AC2-MOD is a technology demonstration of emerging airbeam technology that focuses on manufacturability and reliability. It is currently undergoing customer testing at Aberdeen Proving Ground and has potential for future military shelter programs.

Vertigo Inc. High Pressure Braided Airbeam Structures

Vertigo Inc., located in Lake Elsinore, California, has specialized in the design of inflatable composite structures, airdrop systems, unmanned vehicles, and other customer programs since 1986. The Natick Solder Center has worked extensively with Vertigo Inc. to advance the technology of high-pressure, braided, airbeam-supported structures. It has been long understood that a reduction in airbeam diameter, therefore reducing cost, weight, and cube, requires the use of increased internal pressure. In order to advance beyond the commercially available low pressure inflatable composite structures, the technology of the airbeam fabrication must be redesigned. Through a combination of independent research and development and joint efforts with the NSC, Vertigo accomplished the development of an entirely new airbeam capable of withstanding inflation pressures more than ten times that of previous designs.

Vertigo went beyond the traditional woven airbeam, which is unreliable and unsafe at higher pressures. A braided airbeam was developed using Vectran® around a urethane bladder. The urethane bladder provides exceptional air holding qualities. Vectran® was chosen as the braiding material due to its combination of flexibility and strength. The braided tube is fabricated using continuous fibers with a bias angle optimized for the pressure containment and longitudinal fibers for bending resistance (See Figure 14). The exterior surface of the braided airbeam is coated to protect the fibers from abrasion and exposure to the environment. Through a combination of mathematical modeling, finite element analysis, and physical data Vertigo is able to design an airbeam structure with the optimum beam diameter, inflation pressure, and beam spacing for a variety of applications.

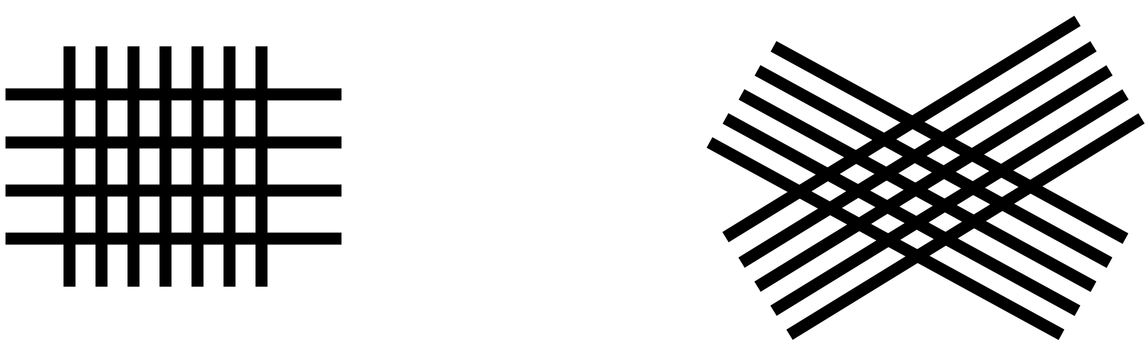

Figure 14. Weave versus Braid.

Chemical and biological contamination can occur at a moment's notice, which is why rapid depolyability is critical in collective protection. Airbeams are particularly attractive for this application because of their reduced weight, cube, and erection requirements compared to traditional rigid frame tents of comparable size. The increased inflation pressure of Vertigo airbeams further reduces these characteristics because smaller diameter beams with increased beam spacing are possible. The developments in the fabrication of braided airbeams allow Vertigo to design shelters large enough to house a CH-47 helicopter or small enough to support far forward medical missions. Large-scale airbeam shelters have been made up to 82 ft. 11 in. wide by 35 ft. 2 in. high by 170 ft. 6 in. long (See Figure 15). The tubes were manufactured on the largest vertical braider in the country (See Figure 16). This shelter,

Figure 15. Wide Span Airbeam

Figure 16. Wide Span Airbeam Loom.

the Aviation Inflatable Maintenance Shelter (AIMS), consists of nine 30 in. diameter airbeams inflated to 80 psi and takes two days to erect. This is much less than the weeks it can take to erect a metal frame structure of comparable size. The smaller airbeam structures, such as the Small Tactical Airbeam Tent (STAT), consist of three 10 in. diameter airbeams inflated to 40 psi. The shelter is semi-cylindrical and measures 22 ft. wide (20 ft. interior) by 11 ft. high (10 ft. interior) by 24 ft. long. The STAT is quite attractive to a variety of CB protected military applications including medical, rest and relief, communications, and command post functions. The shelter skin is designed to interface with standard military equipment such as lights, power supply, and environmental control. The ease of use and versatility of this shelter makes it also viable for homeland defense and civilian applications. The STAT is easily transportable due to its small packing weight and volume (425 lbs. and 74 ft^3).

This structure requires minimal personnel and effort to strike and erect because the airbeams are integral to the shelter skin. Once the shelter is unrolled, it is inflated using a small compressor, and the endwalls are put into place. The system comes with repair patches for any identified punctures, but the beams are removable if needed. The simplicity of the shelter frame allows for simple deployment and minimal maintenance. An experienced crew consisting of four people can erect/strike the shelter in less than 30 minutes. The STAT (See Figure

17) frame consists of only three beams connected by a thin, flexible tube integral to the skin. Valves are placed in this tubing to isolate the pressurized air in each beam.

Figure 17. Small Tactical Airbeam Shelter.

With the use of higher inflation pressures, safety is always a concern. An airbeam inflated to 40 psi contains much more stored energy than one inflated to four psi. Vertigo, taking these concerns into account, has conducted a number of mathematical iterations and full-scale testing to ensure the safety of their structures. The mathematical modeling is used to choose the appropriate airbeam parameters for predicted loads. Full-scale testing is used to validate the numerical calculations and determine the method of failure. Vertical load testing was conducted on STAT airbeams proving that the beams could hold a load over 700 pounds without buckling. This capability more than compensates for a 10 psf snow load. Out of plane bending, over inflation, and puncture tests were also conducted during STAT development. Vertigo designed the airbeam to fail at the fill port during over-inflation. This designed failure prevents potential non-repairable burst damage of the airbeam. In full-scale over-inflation testing the fill port failed at approximately 157 psi and the beam was unaffected. In the event of a puncture or failure in the airbeam itself, failures do not propagate along the length of the beam allowing safe release of the pressurized air. Vertigo over-inflated a STAT airbeam to 80 psi (twice the operating pressure) and punctured it with a knife. The airbeam simply lost pressure rather than bursting like a balloon. The airbeam was repaired using the patch in the field repair kit and used for subsequent testing.

Vertigo has successfully developed the high pressure, braided airbeam, which is more technically advanced than commercially available inflatable composites. Development and improvement work is ongoing between Vertigo and the NSC to mature and transition these technology demonstrations to a military engineering development program. Such collaborations produce more airbeam structures, making them a more affordable advanced technology.

IV. THE FUTURE OF RAPIDLY DEPLOYABLE COLLECTIVE PROTECTOIN SHELTERS

Over the past 40 years collective protection (CP) shelter designs have had tremendous technical advances. The discovery and development of new materials has improved strength and protective capabilities while reducing weight and cost. Structural designs have gone beyond the traditional heavy metal general-purpose tents of the military's inventory. Collapsible rigid frames and pressurized airbeam supported shelters are relatively new technologies, but have proven to reduce strike and erect requirements as well as bulk. These advances are critical in a world where proliferation of weapons of mass destruction continues. The design and fabrication of a CP shelter, whether for military or civilian applications, must account for rapid mobility and deployability requirements. Ideally a CP shelter will pack into a small bundle with all pieces integral to be easily dispersed to the widest dissemination. Strike and erection of the CP shelter will require a minimal amount of time and manpower in order to rapidly respond to chemical and biological warfare agent threats and attacks. Ultimately the shelter will also have CB protective capabilities integral to the shelter skin to eliminate the use of a separate protective liner. This protective skin must survive decontamination, abrasion, and exposure to extreme environmental conditions.

The Natick Soldier Center-Collective Protection Directorate is dedicated to the design, development, and proliferation of the next generation, rapidly deployable, collective protection shelter. Continuous research and development programs with industry partners explore new shelter material technologies to create an effective, lightweight, affordable material. The Inflatable Composite Structures Center of Excellence was founded and staffed to be the leader in airbeam technology. Its objectives include mathematical modeling to design the optimum airbeam frame for various applications, advancing manufacturing technologies, broadening applications, and conducting testing. Joint ventures between the NSC, Federal Fabrics-Fibers Inc., and Vertigo Inc. continuously improve upon airbeam-supported structures to reduce cost and increase reliability. The NSC is also continuously combining in-house engineering design and prototyping capabilities and communicating with commercial shelter manufacturers to find the latest in rapidly deployable shelter technology and transfer it to collective protection applications. Such commercial companies are DHS Systems, Johnson Outdoors, Camel, and Bea Maurer.

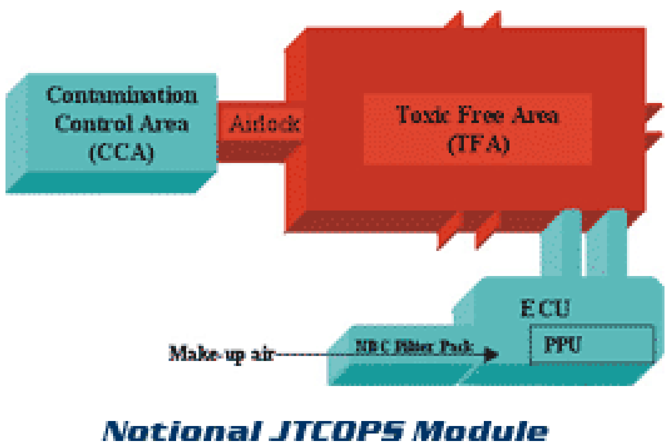

Figure 18.

The Joint Transportable Collective Protection System (JTCOPS) is a joint effort between all branches of the U.S. military to design and fabricate the future collective protection systems. The Notional JTCOPS module is shown in Figure 18. Compared to current systems, this will have increased sustainability, mobility, depolyability, and be affordable.

The NSC Collective Protection Directorate will be at the forefront of the JTCOPS effort, combining the best in engineering research and design to demonstrate a technological leap in the field.

ACRONYMS

AC2-MOD	Advanced Control Center Module
AIMS	Aviation Inflatable Maintenance Shelter
BAS	Battalion Aid Station
CB	Chemical Biological
CBPS	Chemical Biological Protective Shelter
CP	Collective Protection
CPD	Collective Protection Directorate
DCS	Division Clearing Station
DSP	Dimensionally Stable Polyester
ECU	Environment Control Unit
FFF	Federal Fabrics-Fibers Inc.
HMMWV	High Mobility Medium Weight Vehicle
JTCOPS	Joint Transportable Collective Protection System
NBC	Nuclear Biological Chemical
NSC	Natick Soldier Center
NONFESA	Nonlinear Finite Element Analysis
PEN	Polyethylene Napthalate
SBCCOM	Soldier Biological Chemical Command
STAT	Small Tactical Airbeam Tent
TCPS	Trailerless Collective Protection System
TEMPER	Tent Extendable Modular Personnel
THE	Transportable Helicopter Enclosure

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